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ELECTRICAL WELL LOGGING
IN THE EASTERN STATES

By PARKE A. DICKEY
PENNSYLVANIA TOPOGRAPHIC AND GEOLOGIC SURVEY

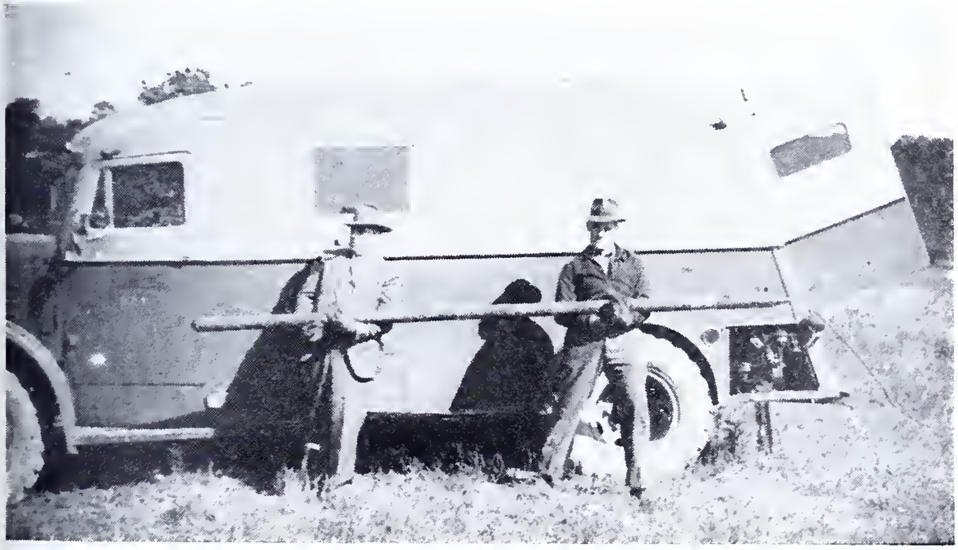

Figure 1. Electric logging truck and electrode.

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ELECTRICAL WELL LOGGING IN THE EASTERN STATES

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INTRODUCTION

Preface

The service of electrical well logging was made generally available to the oil producers of the Pennsylvania region in the spring of 1942. If this service is to be utilized intelligently and fully, the operators and engineers need a clear understanding of the methods, purposes and limitations of the technique and its application to local problems. This paper is an attempt to fill that need, and was written from a purely practical point of view. Discussion of the theory is restricted, and only enough is included to enable the operator to interpret the records he obtains. As a matter of fact the natural phenomena utilized in well logging are very poorly understood, especially the causes of the natural potentials. Although the resistance observations may be explained mathematically, the rather complicated equations can seldom be applied to the solution of practical problems.

This paper was written with the conditions and problems of the Appalachian fields in mind, but it is possible that it may also be useful in other districts. Published articles on electric logging and books on geophysics are for the most part rather inadequate.

As more experience in electrical logging in the Pennsylvania fields is acquired, the applications and potentialities of the method will be better understood. It is hoped that the individual oil producers will make the results of logging on their properties available to the Pennsylvania Geological Survey so that that organization may study and correlate them, and from time to time make the collective experience of the operators generally available.

Development of electrical well logging

During the early years of the twentieth century numerous investigators in Europe and the United States studied the electrical properties of the earth's surface. It was found that various types of rock strata and soils had different electrical resistances. Knowledge of the resistance of the ground is important in the design and construction of grounds for electric power and communication systems, and circuits and apparatus were devised for its measurement. It was found that geological discontinuities could be located by resistance measurements, and that it was possible to find rocks of contrasting resistance even when they were not exposed at the surface. Resistance measurements have been extensively used to locate ore bodies, gravel beds, water-bearing strata, and other geological bodies of economic importance.

In connection with these studies it was also found that electric currents generally exist in the ground, accompanied by small but measurable differences of potential from place to place. These potentials are generally caused by chemical reactions occurring in the ground waters. The corrosion of pipe and other metallic objects is a chemical reaction that is accompanied by an electric current, and the oxidation of certain minerals is a similar reaction.

About 1928 Conrad and Marcel Schlumberger began making electrical measurements in oil wells. The practical utility of such measurements was first demonstrated in the Russian oil fields about 1929, and in Venezuela in 1930. Although electrical measurements were made in oil wells in the United States as early as 1930, it was not until about 1935 that the technique became fully developed and the practice of logging wells became extensive.

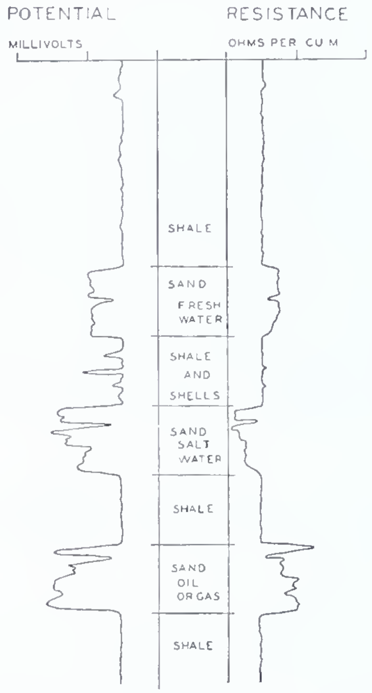

Figure 2. Ideal electric log.

At present the measurement of the electrical resistance and potential of the different strata in an oil well, generally called "electrical logging," is general practice in most of the world's oil fields. Geological information of great importance to the proper development of a field may be obtained by these measurements more easily and cheaply than by any other method.

The first attempts at electrical logging were made in the eastern fields in 1937, when one of the companies specializing in this service made several demonstration runs in the Bolivar, Bradford and Oil City districts. Both the geological conditions and the engineering problems encountered were very different from those of the western fields. Insufficient experimental work was done to determine the possible applications of the method to local problems. Little interest developed among the producers, and the equipment was sent to another district.

In 1940 the Pennsylvania Topographic and Geologic Survey started experiments to determine the applicability of electrical logging to the geological and engineering problems of the Titusville-Oil City district. The results of these experiments were communicated by the Geological Survey to a group of operators at Titusville on July 22, 1941. These operators appointed a committee to negotiate with the well logging companies and to endeavor to obtain for the eastern fields a service that would be adapted to local problems.

Apparatus has been devised for the determination of all sorts of physical properties of the formations in wells. To date only two have been determined on a large scale and have demonstrated their practical utility. These are the measurement of the electrical potentials and the resistance of the various beds. The determination of radio-active emanations such as gamma rays and neutrons has recently been accomplished, and appears to promise much utility, especially in logging cased holes where the iron

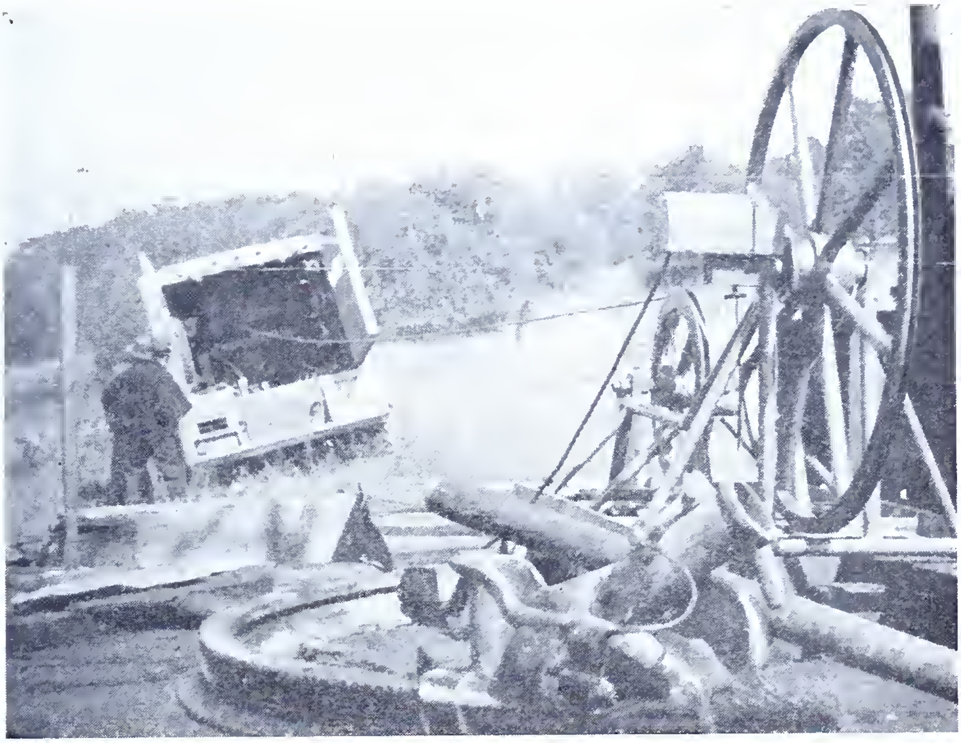

Figure 3. Apparatus used in commercial well logging; showing measuring sheave.

pipe makes impossible the determination of the electrical properties of the formations.

For a more extended discussion of the theories and methods of determining the electrical and other physical properties of geological formations, the reader is referred to recent textbooks on geophysical methods, and the literature and patents quoted therein.[1]

Summary of methods and uses of well logging

The principles of electric logging are very simple, although the apparatus and especially the interpretation of electric logs may become rather complicated. The method consists of determining some of the electrical properties of the strata penetrated by the bore hole. These properties may in some cases be correlated with the geological character of the formations, and in other cases may not. However, the electrical properties vary from one stratum to another, and in two nearby wells if the geological succession is the same the electrical succession will be the same. The two electrical properties most generally observed are the potential and resistance of the strata.

It has been found that a considerable electrical difference of potential, that is, voltage, exists between the sandy beds and shales. The sands are negative with respect to the shales, and the potential may be as high as one or two tenths of a volt. However, a sensitive meter must be used to measure this potential since an ordinary voltmeter has such a low internal resistance that it short-circuits the source of the potential. In practice, the electrode is connected to one side of a recording meter and a suitable ground to the other, and the variations of potential are noted as the electrode is lowered in the well. When the electrode passes a porous sand the indicator needle swings sharply towards the negative, and returns to a rather constant position in the shales.

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[1] Jakosky, J. J., Exploration Geophysics: Times-Mirror Press, Los Angeles, Calif. 1940. Heiland, C. A., Geophysical Exploration: Prentice-Hall, New York, 1940.

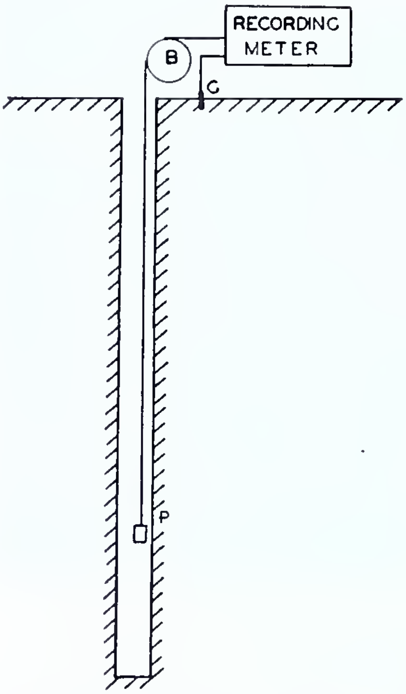

Figure 4. Method of measuring potentials in an oil well.

The cause of these potentials is not well understood. It appears likely that they exist at all times in the rocks, although they are modified by other sources of potential that are introduced when a well is drilled. They may be used to locate accurately the positions of the sands in an oil well, and in some cases will give some idea of the character of the sand.

It has also been found that different rock strata have different resistances to the flow of electric current through them. The particles of clay and quartz have a high resistance, but in the ground they are generally partly or completely saturated with water, and are able to conduct electricity. Fresh water has a very high resistance, which decreases rapidly as the amount of dissolved salts increases until salt water as found in oil wells has a very low resistance. Oil and gas have a very high resistance, and if most of the water in a sand has been displaced by oil or gas, the sand may have a rather high resistance. Shales have a low resistance which is usually quite constant in any one well or district. Fresh water sands may have a resistance as high or higher than oil or gas sands. Salt water sands generally have a resistance even lower than that of shales. Sometimes, therefore, it is possible to get an idea of the fluid content of the sands by means of their electrical resistance.

The natural resistance of the sands is affected, sometimes to a large degree, by the disturbing effects of the water used in drilling the well, which in many cases enters the sand and changes its resistance. Unless a good deal is known of the hydrostatic conditions in the well and the character of the sand from samples or cores, the interpretation of resistance curves is often difficult.

Once a correlation between the electrical properties and the character of the sand is established, it is possible to interpret electric logs, and they provide a cheap and rapid method of obtaining information that is indispensable to the proper development and operation of an oil pool.

As a general rule, shales have a low potential and low resistance, fresh water sands have a moderate potential and moderate resistance, salt water sands have a high potential and very low resistance, and oil or gas sands have a high potential and high resistance. An idealized electric log illustrating these conditions is shown in figure 2. As will be explained more fully later, many factors tend to modify the electrical responses, and the interpretation of electric logs cannot be referred to a standard formula.

In the western fields electric logs are used principally for the location of pay oil sands and for geological correlation. In the past the importance of more information on these points has not been obvious in the Pennsylvania fields. The results of electric logging to date indicate, however, that even with cable tools and cores, very substantial thicknesses of potential oil sands have not been noticed by the drillers, and the general use of electric logs should considerably increase the recoverable oil reserves of the district. It has been found that accurate correlations are essential to intelligent prospecting for sand extensions and new fields, and the sands are so discontinuous that electric logs provide the only means for identifying properly the various productive horizons.

There are other problems peculiar to the older fields of the east for which electric logs seem to provide the cheapest and most practical solution. All records for many leases have been lost. Cleaning out and rehabilitation of old wells is practically impossible without a record of the depths of the productive sands. During the cleaning out operation electric logs may be obtained in old wells and even in wells that have been plugged and abandoned for many years. In some cases important pay sands that had never been recorded during the original drilling have been located by means of electric logs and placed in production.

Secondary recovery methods of producing oil require detailed and accurate records of the wells, especially those that are used to inject gas, air, or water. Electric logs may be used to supplement cores in determining the places to set multiple packers or corrective shots in order to avoid bypassing. Where good correlation between the electric logs and geological properties such as permeability is found to exist, electric logs may reduce the number of wells that it is necessary to core. The determination of the geological properties of the sands, such as porosity, permeability, and oil and water content, is never possible with electric logs alone, although they will almost always distinguish sand from shale. It is possible to note that one type of sand gives a certain response and another type a different one, and to recognize these responses in wells that have not been cored. Electric logs will also locate the positions of the changes in character more accurately than any coring or sampling method. They do not replace cores, but supplement them, and often make it necessary to core fewer wells.

POTENTIAL MEASUREMENTS

Methods of measuring potentials

In recent years several geophysical and oil-well servicing companies have made electrical well logging available in nearly all the oil fields of the United States. The various companies use methods and apparatus that differ slightly, but the plotted logs are similar and in general comparable. The commercial equipment consists of a truck in which are mounted the recording instruments and a winch on which the cable is wound. The truck is backed up near the well and the electrode is lowered into the well on the cable, which is passed over a measuring sheave at the well-head.

Apparatus. The potential differences present in an oil well may be measured by lowering one electrode into a well on an insulated wire, and measuring the potential between the well electrode and a suitable electrode on the surface of the ground (Fig. 4). The well electrode (P) may be a piece of metal, such as brass or lead, enclosed in a sheath or basket so that it does not rub against the side of the hole. Electrical contact with the formations is made through the drilling water in the well. For the surface ground, a similar electrode may be immersed in the mud pit or pile of sand-pumpings. One commercial company uses the metallic sheath on the table.

The wire or cable has sufficient tensile strength to support its own weight and that of the electrode, and the insulation must be able to withstand abrasion and contact with oil. It passes over a sheave (B) at the well-head, which is cut to fit the wire, so that for each turn of the sheave a specified number of feet of wire go into the hole. Attached to the sheave by gears is a counting device so that the depth of the electrode may be instantly read. A properly built sheave of this sort is more accurate and consistent than a steel measuring line. However, since measuring lines are apt to vary, it is desirable to measure the hole with the driller's line and compare it with the electrical measurements. The electric log should then be corrected to correspond with the driller's steel line which will be used in shooting or in setting packers.

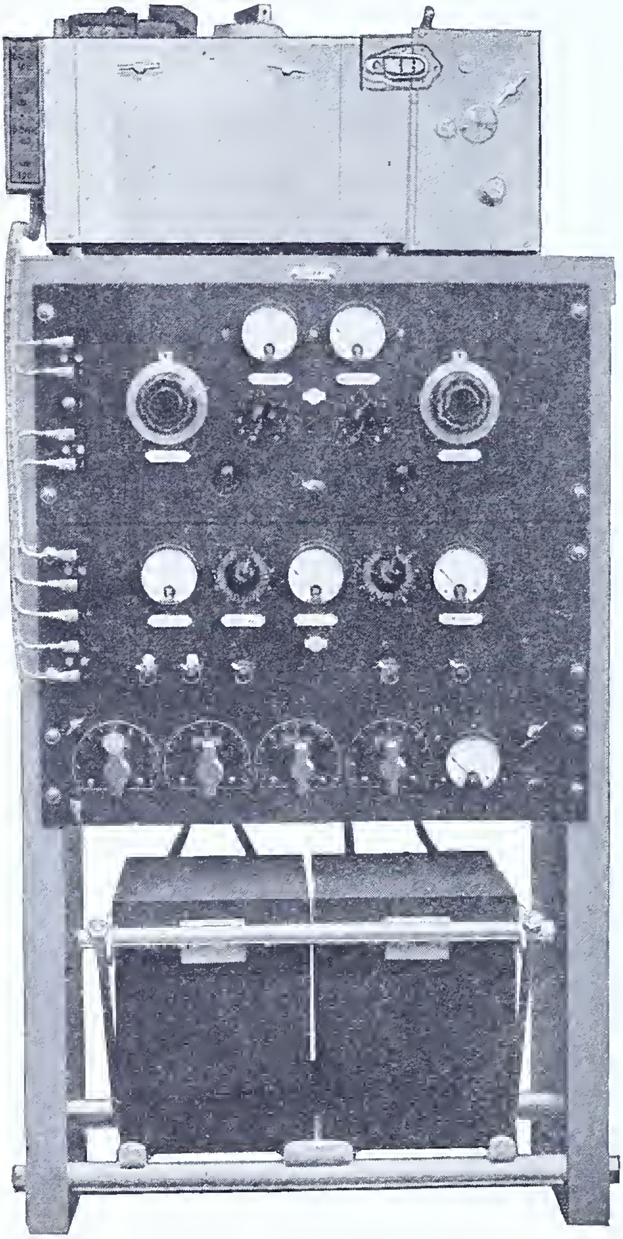

Figure 5. Instrument panel with recording camera on top.

In some commercial outfits an "autosyne" motor is connected to the sheave along with the foot-counter. This is connected electrically to another autosyne motor which drives the recording mechanism. It is a property of these motors that the rotor of the second one turns exactly with the rotor of the first. A set of gears is arranged so that a piece of paper or photographic film is drawn through the recording meter one inch for each ten feet that the wire moves, or one inch for each 20 or 100 feet, as desired.

Although the potential differences amount to one or two-tenths of a volt, the currents they are able to produce are so weak that they can only be detected on a very sensitive galvanometer, and ordinary millivoltmeters are not suitable. They may be measured accurately with a so-called null balance potentiometer. One commercial outfit uses a vacuum tube voltmeter. This is a series of one or more vacuum tubes operating like an amplifier in a radio set. The current produced in the plate circuit depends on the potential imposed on the grid circuit which has an exceedingly high resistance. It is thus possible to amplify and measure the potentials without diminishing them by drawing any current.

As a rule, the amplified current which depends on the potentials in the well is connected both to an indicating meter which the operator can watch, and a recording meter. The latter is like an ordinary galvanometer, except that instead of an indicating hand on a dial the coil is attached to a tiny mirror. A beam of light is directed to the mirror, and reflected by it on to a strip of photographic film passing over rollers. The film is driven by the measuring sheave by means of a direct connection, or by the autosyne motors described above. Contactors make supplementary light flashes which record as lines on the film every two or every ten feet. In this manner a chart is automatically recorded which shows the electrical properties plotted against depth. The trucks are equipped with dark rooms so that the operators can develop the film immediately and give the operator the results of the measurements almost as soon as the run is completed.

Precautions. Great care must be used in the design, construction, and operation of the apparatus to avoid electrical leakage. There are several sources of potentials which do not depend on the geological conditions, and it is necessary to eliminate these or at least hold them constant.

When any metal is placed into a solution of a salt in water the metal acquires a potential difference with respect to the solution. This effect is similar to the formation of electrical potential in a dry cell or wet battery. The value of the potential difference depends on the metal, and the nature and concentration of the salt. A potential difference therefore exists between the electrode and the well water, but if the electrode is protected from abrasion it is usually fairly constant, and the potentials present in the different strata will be superimposed on it. Any change in the surface condition of the metal, such as a change in the character of solution in which it is immersed, or polarization caused by the passage of a direct electric current, will change the metal-liquid contact potential. A frequent precaution is to immerse the electrode in the drilling water for a short time before logging, so that the contact potential of the electrode assumes its constant value before it is run into the well.

Frequently non-polarizing electrodes are used. The most common form of these consists of a porous clay pot, in which is a solution of copper sulphate. Immersed in the solution is a bar or sheet of pure copper, which constitutes the electrode. The potential difference between a pure metal and a pure solution of a salt of the same metal is small and constant.

If the concentration of the water in the well changes, the potential difference between the electrode and the water will change, even when a non-polarizing electrode is used. If the composition of the drilling water is not the same throughout the well, this change will cause a shift in the curve. Changes in composition of drilling water occur frequently in holes drilled with cable tools, especially near the bottom.

Strong potentials in the ground are frequently found in the vicinity of an oil well, caused by the corrosion of the casing in the well and the pipe racked on the surface. The effect of these can be eliminated by means of a supplementary "bucking" potential introduced into the circuit. They can also be avoided by using the metallic sheath of the cable as a ground in place of a surface ground.

Causes of Potentials

There are three principal causes of the potentials existing in an oil well.

Natural potentials. It has been demonstrated that potential differences exist naturally in the ground at certain points, particularly at geological discontinuities, such as the boundary between a sand and a shale stratum. It is probable that these natural differences of potential are always present, whether or not a well is drilled, and the sandstones are usually negatively charged with respect to the shales.

Little is known of the cause of these natural potentials, and their importance has only recently been recognized. In most published articles on electric logging the potentials have been ascribed entirely to filtration and concentration potentials, which will be described below. Recent work seems to indicate that the natural potentials existing in the ground, regardless of whether or not a well is drilled, are the major source of the potentials measured in electric logging. The natural potentials have been observed during surface resistivity measurements where no well was present.[1] They have also been noted in mine shafts. It is possible to measure the potentials in an oil well that is empty of liquid by means of a wall contactor.[2] The logging of empty holes is still in the experimental stage, and such logs have only recently been made available on a commercial basis.

When logs are made in wells filled with water or drilling mud, the total potentials are modified by the chemical and physical reactions that take place between the well water and the water in the formations.

Filtration potential. If a dilute solution of some salt in water is placed in two adjacent vessels which are separated by a porous membrane, and if a potential difference is applied to two electrodes, one in each of the vessels, it will be found that the solution will move through the porous membrane towards one of the electrodes. This phenomenon has been called electro-endosmosis, and has been extensively studied. The reverse of this action frequently takes place in oil wells. If the hydrostatic pressure of the drilling water in the hole is higher than the pressure of the oil and

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[1] Lee, F. W., The possibility of electrical stratification in the earth as disclosed by surface measurements of currents and potentials: Trans. Amer. Geophysical Union, Terrestrial Magnetism and Electricity, 1939, pp. 383-389.

[2] There are many advantages in being able to measure natural potentials in empty holes, especially holes drilled by cable tools. Filling the hole with water is frequently objectionable, especially in gas wells. The water tends to enter the pore spaces of the sand and reduce its permeability to oil or gas. Unless the pressure within the sand is high enough to expel the water, the productivity of the well may be seriously damaged.

From preliminary experiments conducted in the spring of 1942 by the Pennsylvania Geological Survey, it appears that more detailed logs can be obtained in an oil well empty of liquid than in a well containing water. A potential log was obtained with an improvised wall contactor, and when it was compared with a diamond core it was found that sharp changes in potential occurred in sandy beds only an inch in thickness. It seems probable that with improved apparatus it may be possible to determine the exact top and bottom of sandy horizons within one inch or less. This accuracy is of great importance in corrective shooting and setting packers in input wells.

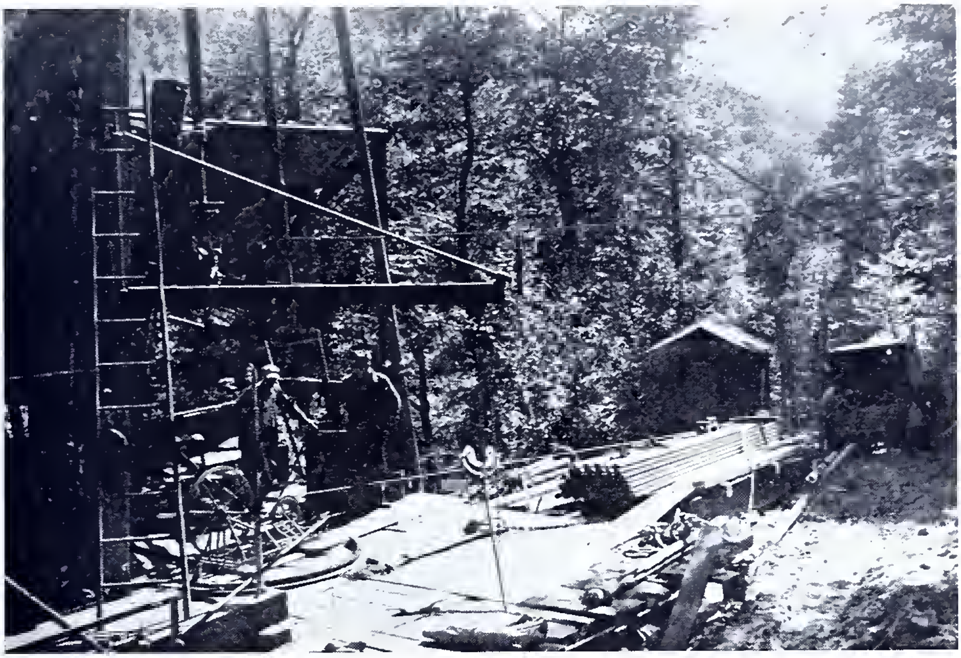

Figure 6. Electric logging a well in McKean County.

connate water in the sand, the water in the hole will filter into the sand. This causes a small potential difference, which, in wells, is generally negative in the drill hole and positive in the sand.

Formulas relating the magnitude of the filtration potential to the pressure differential and the physical properties of the liquid and solid filter have been presented in works on electrochemistry and geophysics. It is very questionable whether they can be applied to the filtration potentials as measured in oil wells. The actual potential difference could be measured only if one electrode were placed in the well opposite the face of the sand and the other electrode back in the sand. The portion of sand in which the second electrode was located would have to be isolated from any connection with the water in the well except through the sand face. Neither of these conditions can be fulfilled in an oil well. The actual value of the filtration potential probably is low, and it is seldom or never possible to distinguish it from the other sources of potential.

The other sources of potential are weak in fresh water sands and in sands that have been flushed by fresh water, such as those in the vicinity of a water input well. It was found that in a well which had been used as a water input well in the Bolivar field (N. Y.) for several months, the potentials opposite the sands increased more than those opposite the shale as the pressure of the water in the hole was increased. This change in potential may have been caused largely by filtration potential effects. In most cases changing the pressure of the water in the well has little or no effect on the potentials.

Since the magnitude of the filtration potential depends, among other things, on the rate at which the drilling water is entering the sand, it has been stated that the value of the potentials depends on the porosity and permeability of the sand. At one time it was thought that the filtration effect was the principal source of the potentials, and the potential log is still occasionally called a "porosity" log. In the Venango district of Pennsylvania there seems to be an important relation between the sand permeability and the magnitude of the potentials as determined by cores or packer tests (see below), but it is very unlikely that this relation is dependent on the filtration potential effect.

When the water is entering the sand the filtration effect causes the water in the well to be negative with respect to the water in the sand. If the water is coming out of the formation the water in the hole should become positive. It has been stated that high-pressure water or oil and gas sands may be recognized by their potentials. It is very unlikely that this is possible, at least in Pennsylvania, where other sources of potential are much larger than the filtration potential. In fresh water sands, however, where the other sources are small, positive potentials have been noted opposite porous sands where fresh water was discharging into the well. Such a positive potential is shown at a depth of 62 feet opposite a water sand in the Atlas well (fig. 12).

Solution concentration potentials. If two solutions of the same salt but of different concentration are placed in a vessel and separated by a permeable barrier, it is found that there will be a difference of potential between them. In solutions of sodium chloride in water the more concentrated solution is positive with respect to the weaker solution. This condition commonly exists in an oil well, where the water used in drilling is less concentrated than the salt water associated

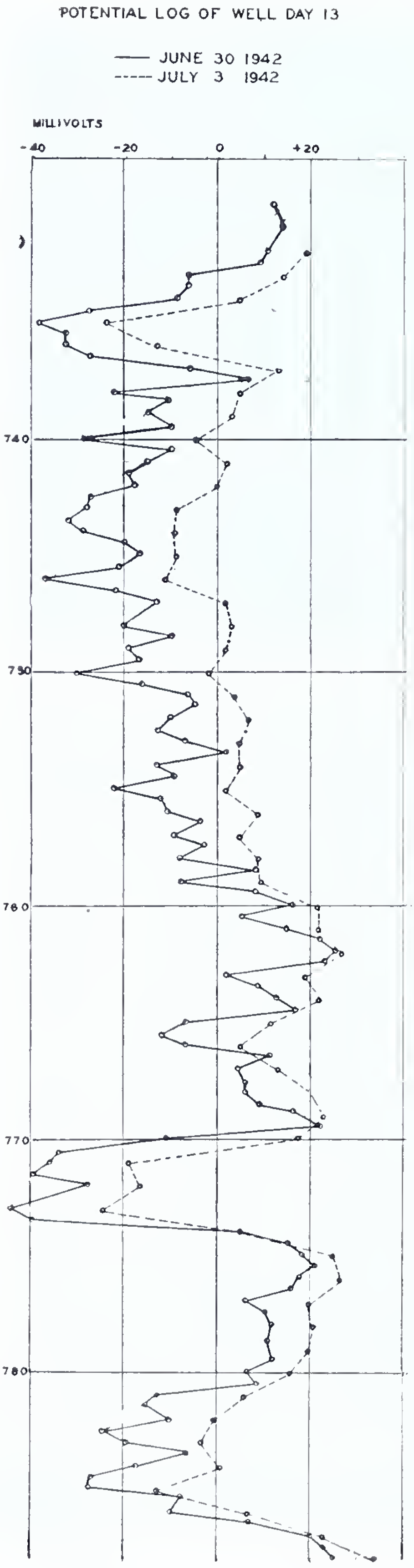

Figure 7. Potential log of well Day 13.

Showing deterioration in amplitude and detail of potentials after four days with fresh water standing in hole.

with the oil in the sands. The water in the hole thus acquires a negative charge with respect to the surrounding material.

The theoretical value of this potential may be easily computed from the concentrations, but like the filtration potential, it is impossible to measure it in an oil well. It is impossible to place an electrode back in the sand isolated from any connection with the drill hole. If the well water is entering the sand the contact between the well water and the formation water, where the difference of potential exists, will gradually move back into the sand and become diffuse. This will tend to reduce the concentration potentials.

It has been noted in the Pennsylvania fields that if fresh water is allowed to stand in a well for a period of time the potentials diminish in value, and the variations tend to smooth out. This is probably in part due to the entrance of the fresh water into the sand, which diminishes the concentration potentials. The entrance of fresh water may also diminish the natural potentials. A well logged every day for four days showed a progressive deterioration in both amplitude and detail of the potential curve (Fig. 7).

Interpretation of Potential Curves

The customary method of plotting potential curves is to make the vertical or ordinate line represent the well, and the abscissa or horizontal distances proportional to the potentials. The vertical line is laid off in feet at any desired scale. If the well is deep and a general picture is desired, it is usually laid off 100 feet to one inch. In detailed work in shallow wells twenty feet or ten feet to the inch are commonly used. The potential measurements are then plotted on the *left* side of the line representing the well, with increasing *negative* values towards the left. As a rule the scales used are between 20 and 60 millivolts per inch. Frequently two potential logs on different scales are plotted on the same chart. The normal or usual log shows the potentials throughout the whole well on a scale of 40 or 60 millivolts per inch. The "amplified potentials" are the same values plotted on a scale of 15 to 30 millivolts per inch opposite the sandy formations only.

As a rule the potentials measured in the shales are approximately the same throughout the entire hole. The average potential in the shale is called the "shale base line." The potential of the sandy formations is nearly always more negative than that of the shales. Sand beds will therefore be shown on the curve as maxima or peaks which stand out to the left of the "shale base line." As a rule, the height of these peaks is approximately the same throughout the well, except that thin sands or shaly sands may show maxima lower than the average of thick and porous sands. It has been found that in Pennsylvania the permeability of the sand is frequently reflected in the amplitude of its potential; the more permeable sands having the more negative potential. There appears to be a saturation point, beyond which a more permeable sand does not have a greater potential.

As explained above, the causes of the natural potentials in the strata are very poorly understood, and the interpretation of the potential curves must be based on experience obtained by comparing electric logs with cores in the same field. The following observations seem to be true in Pennsylvania, and in general, in other districts also.

(1) A more permeable sand has a higher negative potential.

(2) The more salty the water in the sand the higher negative will be its potential.

(3) The more salty the water in the hole the lower will be the negative potential. This is because, (a) there will be less contrast between the well water and water in the sand and therefore less solution concentration potential, and, (b) the saltier the drilling water the more conductive it will be, and therefore it will tend more to short-circuit the differences in potentials between the sands and shales.

(4) If the diameter of the hole becomes larger (as in a shot-hole or "cave") the potentials will be smoothed out and reduced because of the increased short-circuiting effect of the drilling water.

(5) It has been stated that increasing the head of water in the hole increases the negative value of the potentials because of the increased filtration effect. This has not been found to be true in Pennsylvania unless the sands contained fresh water, either naturally in near-surface sands, or because they had been flushed by fresh water in flooding operations.

If the shale base line is taken as zero, the negative peaks opposite the sand may be classed as low, medium, and high. In Pennsylvania, a maximum of 10 to 20 millivolts above the shale base line would be considered low, 20 to 50 millivolts medium, and 50 to 200 millivolts high. However, the height should be considered relative to the other peaks in the same hole, as the absolute potential differences will vary from well to well, depending on the complex factors described above.

A potential log alone will almost always distinguish sand from shale. No interpretations regarding the character of the sand or its fluid content are possible except in districts where correlation of electric logs and core analyses has been established. The resistivity log, to be described next, complements the potential log and assists in its interpretation.

The following table lists the types of formations that have given low, medium, and high potential peaks in Pennsylvania.

Interpretation of potential peaks.

Low

Shale
Hard sandy shale or shaly sandstone
Limestone or limy sandstone
Fresh water sand
Oil, gas, or salt water sand thoroughly invaded by fresh water.

Medium

Relatively impermeable oil or salt water sand
Brackish or fresh water sand
Thin oil or gas sand (if peak is thin)
Thin salt water sand (if peak is thin)
Oil or gas sand invaded by fresh water

High

Salt water sand
Impermeable salt water sand, discharging no water in hole
Oil sand
Gas sand

RESISTANCE MEASUREMENTS

All substances conduct electricity, although some are much better conductors than others. Copper is an excellent conductor of electricity; glass and rubber are very poor conductors and are usually referred to as nonconductors or insulators. The ease with which electricity flows through a conductor is called conductance, or inversely, the difficulty in producing a current in a conductor is called the resistance of the conductor. The resistance of a conductor determines the potential or voltage required to produce a given current through it. If a wire has a high resistance it requires a high potential difference between its ends to produce a current of one ampere, while if it has a low resistance only a small potential difference will produce the same current. These relationships are expressed by Ohm's law, which states that the current in any conductor (in amperes) is equal to the potential difference between any two points (in volts) divided by the resistance between them (in ohms). This expression is usually written $I = \frac{E}{R}$.

The resistance of a conductor made of any given material depends also on its shape and dimensions. The resistance of a wire, for example, varies directly as its length and inversely as its cross section. The specific resistance, or resistivity, is a property of any material which is independent of its dimensions. The resistance of a wire, therefore, is determined by the resistivity of the material, its length, and its cross section in the following manner:

$$R = P\frac{l}{A}$$

where $R =$ resistance
$P =$ resistivity
$l =$ length
$A =$ cross section

Different types of rock strata encountered in the ground have different resistivities. The particles of clay and quartz that make up sedimentary rocks such as are found in most oil wells have, in their dry state, a very high resistivity. However, in the ground they are usually partly or completely saturated with water. The resistivity of water depends on the amount and kind of salt it contains in solution. Pure water has a very high resistivity, ordinary fresh ground water has a moderately high resistivity, and salt water such as is usually associated with oil has a very low resistivity.

The measurement of the resistance of earth strata is not as easy as the measurement of the resistance of small metallic conductors such as wires. When a current is introduced into the ground at two points the lines of

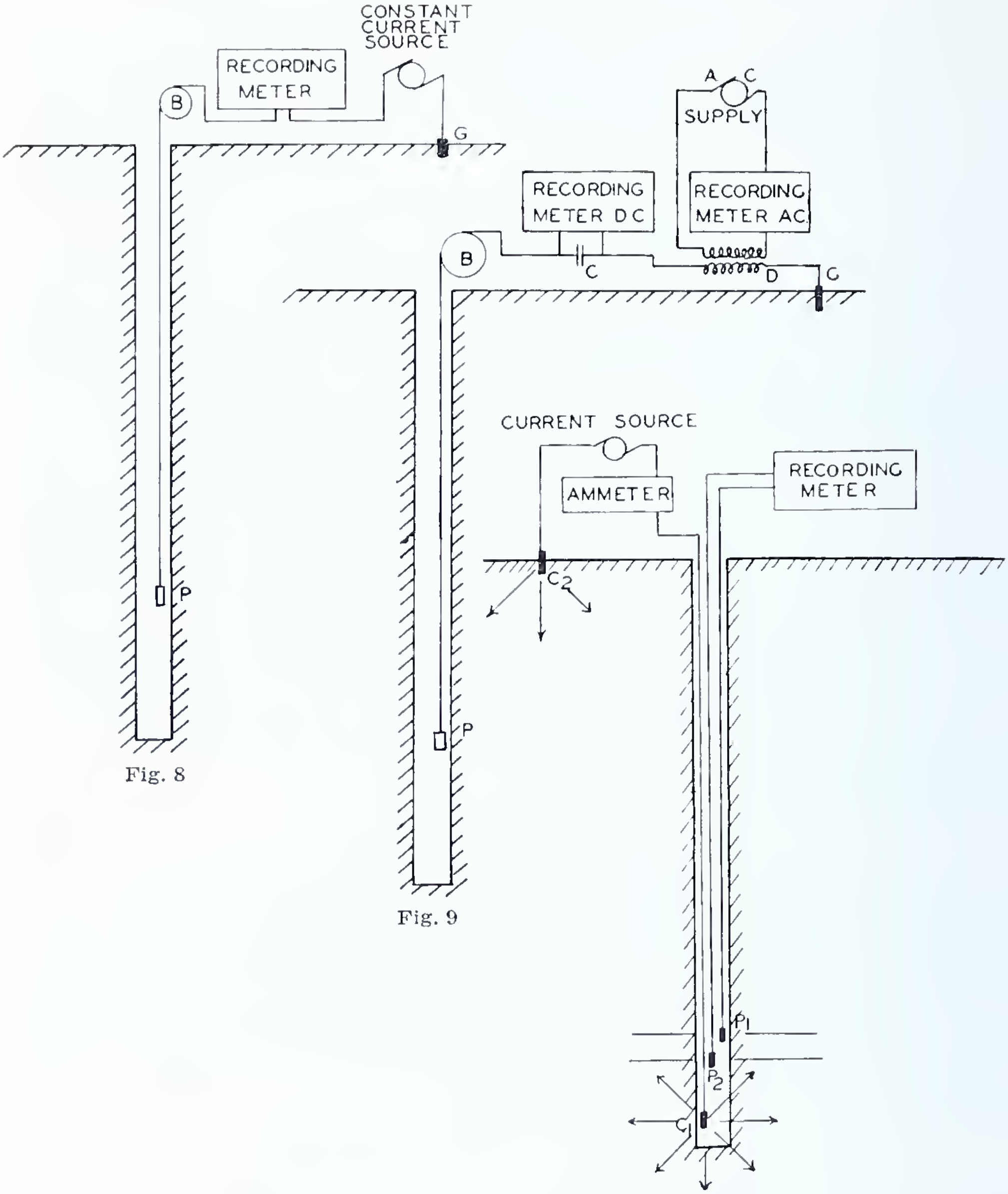

Fig. 8

Fig. 9

Fig. 10

Figure 8. Method of measuring the resistance of strata in an oil well.

Figure 9. Method of measuring resistance and potential simultaneously with the same electrode.

Figure 10. Method of measuring resistance in an oil well using four electrodes (only three of which are lowered into the well.)

current flow do not all run directly from one point to the other, but spread out in all directions almost equally, finally curving around and running into the other point from all directions. When the lines are crowded, as in the vicinity of the points or electrodes where the current is introduced, the current density is intense and the potential differences in the ground are high. At intermediate points where the current is spread out over a path of large cross section the current density is low, and the potential drops are low. Ohm's law holds strictly true, and the higher the resistance of the ground the greater is the potential difference required to produce a given current. The flow lines are not parallel, as they are in a cylindrical or bar-shaped conductor, and although the resistance may be easily measured, it is difficult to calculate the average cross section and length of the paths of current flow. For that reason, it is possible to determine the resistivity of the ground only where a large volume surrounding the electrodes is uniform in resistivity.

The material surrounding the electrodes in an oil well seldom is uniform. There are thin beds of different properties, and rarely does the water in the well have exactly the same resistivity as the surrounding beds. As a rule, it is necessary to assume that the material is uniform or homogeneous, and to calculate what the resistivity would be if this assumption were true. The formulas used depend on the geometry of the current flow lines, which is of course dependent on the number and spacing of the electrodes. These calculated values may be called "apparent resistivity" values. They are usually a fair approximation to the true resistivity values unless the water in the hole has a very different resistivity from that of the formations, or unless the beds are thinner than the electrode spacing. Since the resistance between any two electrodes can always be measured easily and accurately, although the resistivity can seldom be determined, it is considered preferable to call this type of well log a "resistance" instead of a "resistivity" log as is frequently done. If alternating current is used it may properly be called an "impedance" curve. Impedance is the effective resistance of a circuit to alternating currents. With the frequencies and circuits commonly used in well logging the reactance is small, and the impedance is practically the same as the direct current resistance.

Methods of measuring resistance

The simplest method of measuring the resistance of strata in an oil well is shown in Fig. 8. A supply of current that will maintain a constant voltage is connected on one side to a ground and on the other, through a recording meter, to an electrode which is lowered into the well. The amount of current that will flow by reason of this voltage will be determined by the resistance of the circuit, and may be measured by an ammeter. The resistance of the circuit is equal to the sum of the resistances of the different components of it. These may be listed as the resistance of the cable and connecting wires, the resistance of the battery or generator, the resistance of the meter, the resistance of the surface ground, the contact resistance of the well electrode, and the resistance of the current path through the earth from the well electrode to the surface ground. All of these but the last will remain constant as the electrode is slowly lowered into the well. The resistance of the current paths between the well electrode and the surface ground is determined in large part by the resistivity of the material in the immediate vicinity of the electrodes. This is because the current is concentrated in the vicinity of the electrodes, and a change in resistivity in that region has a great effect on the total resistance. Farther away the current is spread out over a greater cross section and the resistance of this portion of the path accordingly is low. It is impossible to define exactly the volume where the main effect of resistivity changes is felt, but it has been determined experimentally that it is within about one foot of the electrode. As the electrode is lowered, therefore, the only cause of fluctuations of current in the circuit will be changes in the resistivity of the strata within a foot or so of the moving electrode.

Instead of measuring the current changes in a power supply that maintains a constant voltage, it is equally possible to use a source of constant current and measure the voltage changes necessary to maintain that current. If alternating current is used it is possible to measure the potentials and the resistances of the various strata at the same time with the same electrode. A diagram of how this is done is shown in figure 9. A constant supply of alternating current is fed into the logging cable and electrode and a ground by means of a transformer. The recording meter measures the resistance of the circuit, but is not affected by the ground potentials, which are direct current and can pass through the transformer secondary to the ground, but not into the transformer primary circuit. The alternating current passes through the condenser C but the direct current is unable to do so, and is forced to pass through the direct current recording meter, where the potentials may be read. This meter is not affected by alternating current. Both the resistance and potential meters record on the same strip of film, and both logs are obtained during the same run.

The fact that the material within one foot of the bore hole causes most of the changes in the resistance curve is advantageous because beds less than a foot thick can be located. In other respects it is not so desirable, since the water in the well may have invaded the sand, pushing the formation liquids back so that their presence does not affect the resistance curve. It is therefore sometimes desirable to measure the resistance farther back in the sand, even though the position of the beds cannot be located as accurately.

This may be done by using four electrodes, as shown in figure 10. A constant source of current is introduced into the well at the electrode C_1 and into the ground at the surface at electrode C_2. A short distance above the current electrode C_1 (say five feet) is placed another electrode P_2 and above it (say two more feet) is a third electrode P_1. The surface electrode is so far away that the current flows out from C_1 through the ground in all directions equally. A portion of the current will thus be flowing upward through the strata opposite the interval between P_1 and P_2. The resistance of the strata between P_1 and P_2 may be determined by the potential difference between the bottom and top of the strata divided by the amount of current flowing upwards through them. The potential difference may be measured by connecting a meter to the electrodes P_1 and P_2. If the current is kept constant, the potential difference will be directly proportional to the resistance of the effective current path. It has been found that the effective current path is approximately as wide as the distance C_1-P_2, so that if this distance is five feet, the resistance of the strata between P_1 and P_2

as far back from the hole as five feet will affect the readings.[1] It is thus possible to get an approximate value of the resistance of the strata a considerable distance back from the hole. In doing so, however, small vertical variations are eliminated, and the top and bottom of the resistant bed are often not well defined (see footnote). Therefore it is usual practice to make a resistance log with both a single-electrode and a multiple electrode configuration, the former giving resistance changes near the well, and the latter giving an idea of the resistance several feet back from the well. The multiple spaced electrode curve is usually called the "third curve."

Causes of resistance changes

WATER IN FORMATIONS

Since most rocks (except the metallic ores) have a rather high resistivity when dry, the conduction of electricity through the ground takes place largely by means of the water contained in the pore spaces of the rocks. Absolutely pure water has a very high resistivity, but most ground water contains considerable quantities of dissolved salts. Conduction of electricity through a salt solution in water depends on the amount and kind of salt that is dissolved.[2]

The resistivity of a sandstone or shale thus depends almost entirely on the amount and salinity of the water that it contains. Shales have a considerable porosity, although little or no permeability, and generally contain considerable quantities of water. They are thus usually rather good conductors. In Pennsylvania the shales have a resistivity ranging between 20 and 100 ohm-meters. Generally the resistivity of the shales is higher near the surface, probably because the contained water has been somewhat diluted by osmotic action and is less saline. Unconsolidated or partly con-

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[1] It is frequently implied that with this electrode configuration it is possible to measure the absolute resistivity of a shell of material around the current electrode, whose radii are C_1-P_1 and C_1-P_2. If C_1-P_1 is r_1, C_1-P_2 is r_2, the current through C_1 is I, and the difference in potential is E, the formula for the resistivity, P is

$$P = \frac{4\pi E r_1 r_2}{I(r_1 - r_2)}.$$

This is, of course, true only where all the material surrounding the electrodes is entirely homogeneous, a condition that seldom or never occurs in an oil well.

Actually, the potential drop between P_1 and P_2 is affected to different degrees by the resistivity of the different materials surrounding the electrode configuration. If the water in the drill hole has a lower resistivity than the formations, the potential drop along the drill hole will be less in a corresponding distance than in the formations, and the apparent resistivity will be less than the true. The resistivity of the strata between P_1 and P_2 probably affects the potential drop between P_1 and P_2 more than the resistivity of any other part of the surrounding material. However, the resistivities of other volumes will have important effects. If there is a highly resistant bed below the current electrode, the current flow will not be strictly radial, but will tend to be more intense upward. The current density above the electrode will be increased, and correspondingly the potential drop between P_1 and P_2 will be increased. If there is a resistant bed between C_1 and P_1, but not extending much below C_1, the opposite effect will occur, and most of the current will flow downward, reducing the potential between P_1 and P_2 and causing an apparent drop in resistance as the potential electrodes approach the resistant bed, or before they pass through it, depending upon its thickness. No extended discussion will be given here, and the reader is referred to Heiland, C. A., "Geophysical Exploration," p. 828, and Hummel, J. N., Beiträge angewandten Geophysik, vol. 6, no. 1, pp. 89-99 (1936).

[2] Conduction of electricity through a solution of a salt in water is called electrolytic conduction, and differs in some important respects from metallic or electronic conduction. The most important difference is that in the first type the electric current is not associated with the movement of any ponderable quantity of matter, while in electrolytic conduction the passage of the current is accompanied by a transportation of matter. For the purpose of this discussion it is not necessary to distinguish between metallic and electrolytic conduction. The conduction of electricity through a salt solution is explained by the *theory of electrolytic dissociation,* which is discussed in any modern textbook on chemistry.

solidated sediments like those of the Gulf Coast have a lower resistivity, doubtless because they are more porous and contain more water per unit volume. In any one well the resistance of the shales is usually fairly constant, and forms a convenient reference or "shale base line" to which the resistance of the sands may be referred.

Sandstones may have either a high or low resistivity depending on the water they contain. If the water is fresh the resistance of the sandstone is high, but if the water is salty the resistance may be very low. Fresh water sands thus show a high resistance in electric logs, and may have resistivities ranging up to several hundred ohm-meters. Sandstones fully saturated with strong salt water may have resistivities of less than 10 ohm-meters.

Oil and gas themselves have very high resistivities, and sandstones well saturated with either generally have a high resistivity. Practically all oil sands also contain considerable quantities of connate salt water, even though they may produce only clean oil. The resistivity of an oil sand therefore depends on the amount and salinity of the water present rather than on the amount of oil or gas that it contains.

It has been shown[1] that the resisitivity of sandstone will depend on (1) the resistivity of the salt water, (2) a factor depending on the porosity and permeability of the sandstone, (3) the saturation of (that is percent of porosity occupied by) the water. If any two of these values are known the third may be calculated. The resistivity of the water may be determined by measuring the resistivity of the water produced with the oil, the factor may be determined by tests on cores, and therefore it might be possible to determine the saturation of water in the sand from resistivity measurements. This has been done in some cases, but in general it is not possible. It is seldom possible to measure the true resistivity of the formation, as explained above, and in Pennsylvania, at least, the porosity and permeability, and therefore the formation factor, change widely within short distances in the same sand body.

WATER IN BORE-HOLE

Like the potential measurements, the resistance measurements in oil wells depend partly on the natural conditions existing in the geological strata in their undisturbed state, and partly on the disturbing effects of the water in the drill hole. These latter are very important, and must be taken into account in interpreting resistance logs.

Salinity of water in hole. The resistance changes measured with a single electrode depend on the changes of resistivity of a volume around the electrode only about one foot in radius, and therefore such measurements are greatly affected by small changes in the salinity, and therefore the resistivity, of the drilling water. Increasing the salinity of the drilling water decreases its resistivity, which decreases the resistance values as measured by the electric log. Changes in the composition of the drilling mud in holes drilled with rotary tools are seldom found, since the mud is continuously circulated from the bottom of the hole upward. In cable tool holes, however, it is practically impossible to get the water in the hole constant in salinity from top to bottom. It has been usual practice in

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[1] Archie, G. E., Am. Inst. Min. Engrs. Pet. Dev. & Technology, vol. 146, pp. 54-62 (1942).

Pennsylvania to bail the hole completely dry, and then run in the required amount of fresh water as quickly as possible from the water tank. During the period that the well is empty the fluids in the sands tend to run into the hole. Even hard sands that are reported by the driller to contain no water usually discharge a little water, which trickles down along the walls of the hole. Almost always there will be some salty water at the bottom of the hole. When the fresh water is run in, it mixes with the water on the walls and in the bottom. When resistance measurements are made, changes in the salinity of the water in the hole are noticeable as shifts in the average resistance (or the shale base line). These may be gradual or sharp, depending on the amount of mixing of the fresh and salty water.

If the bottom of the sand whose detailed electric log is required is within a few feet of the bottom of the hole, as is usually the case, it is a good plan to run the bailer up and down opposite the sand ten or twenty times in order to mix up the water near the bottom and get the column of water opposite the sand of as uniform composition as possible. If, however, it is desired to locate where water is coming into the hole, it is well not to disturb the column any more than necessary, but to look for the place below which the average resistance values decrease, since it is there that the water is entering.

Pressure of water in hole. After the water is run into the hole, it will penetrate the sands or not, depending on whether its hydrostatic head is greater or less than the pressure in the formations. In the depleted sands of Pennsylvania the formation pressure usually is low, and the drilling water tends to enter the sand under a comparatively low head. If fresh drilling water invades a salt water sand it will raise its resistivity, and a water sand may thus be erroneously interpreted to be an oil sand; or the drilling water may invade an oil sand, picking up salt as it goes, and becoming salty. It will thus saturate the oil sand with brackish water, and the sand will then have a comparatively low resistance, and may be interpreted erroneously as a water sand. Many of the most productive sands in the Oil City-Titusville district are very coarse and permeable, and contain a large amount of water, most of which remains from old accidental water floods. In addition the pressures are low, so that the drilling water tends to enter the more permeable parts. (See Fig. 19.) The water originally in the sand plus the water that enters while drilling combine to make the resistivity of the permeable sand very low, and the resistance curve may show a low opposite the best part of the sand. The "third curve" taken with multiple electrodes is very useful in determining the amount of invasion of the sands by drilling water.

Diameter of hole. If the hole is considerably enlarged and irregular in diameter, as in a shot hole or cave, the resistivity of the formations will have a smaller effect and the drilling water will have a large and variable effect on the resistance curve. In such cases the curve may reflect more the changes in diameter of the hole than the changes in resistivity of the beds, and interpretation will be impossible. The third curve may be helpful when the hole diameter is irregular, as it is less affected by the resistance and diameter of the column of drilling water.

Interpretation of resistance curves

Resistance curves are plotted opposite the potential curve on the same strip. They are plotted to the right of the vertical line representing the well, with increasing resistance to the right. In an oil sand section, the sands generally have both high potential and high resistance, so the curves are nearly mirror reflections of each other.

Although the resistivity of the formations depends on their fluid contents, it will be seen from the foregoing that the measurement of the resistivity of the formations in their natural state is seldom possible. Consequently the interpretation of resistance curves is often difficult and sometimes impossible. A good understanding of the probable character of the formations and the hydrostatic conditions in the hole is always necessary.

Since the shales usually have a rather uniform resistivity they give a rather smooth and uniform resistance curve, and their values provide a shale base line to which the resistance of the sands may be compared. Shifts in the base line are easily noted, and may be caused by either a change in the salinity of the drilling water or a change in the hole diameter. The sands will have resistances either less than the shale, slightly greater than the shale, or much greater than the shale.

If the sands have a resistance less than the shale base line it indicates that they are well saturated with salty water. This water may have been originally present in the formation, or it may have run in while the well was drilling. A knowledge of the character of the sand and its permeability will assist in deciding which is the case, as will also the third curve. Conversely, the location of permeable beds can sometimes be made by noting where the greatest invasion of water has taken place.

If the resistance of the sands is slightly higher than that of the shales, it indicates that they contain a small amount of salty water or a rather large amount of brackish water. Moderate amounts of salty water are generally present in "hard" and "dry" sands of low porosity, and in poorly saturated oil or gas sands. Large amounts of brackish water occur especially in oil sands that have been flooded, either during drilling or by another well, accidentally or intentionally. Such sands may frequently be encountered in the partly flooded districts of the Bradford field. A third possibility is that the sand actually has a high resistivity, but is so thin that only a moderately high resistance is recorded on the curve.

If the sand has a very high resistance, it indicates that it contains large amounts of fresh water or comparatively small amounts of salt water. The former is the case in the upper water sands which must be cased off near the surface. It is also the case in certain flooded sands at Bradford, where sufficient flood water has passed through the sand to remove completely the salt originally dissolved in the connate water or crystallized in the pores. Well-saturated oil or gas sands usually contain only small amounts of salt water, so that these generally show as resistance highs, unless they have been invaded by drilling water.

The potential log is usually of great assistance in interpreting the resistance log. Since fresh water sands generally have a low potential, they may be distinguished from oil sands, in which a high resistance is generally accompaned by a high potential.

Interpretation of potential peaks

Less than shale base line

VERY LOW RESISTANCE

Salt water sand

LOW RESISTANCE

Salt water sand
Brackish water sand
Oil and gas sand containing much connate water
Oil and gas sand invaded by water

More than shale base line

MEDIUM HIGH RESISTANCE

Sandy shale
Sandstone of low porosity
Fresh water sand
Oil or gas sand invaded by fresh water
If peak is thin: thin high resistivity sand

HIGH RESISTANCE

Oil sand
Gas sand
Fresh water sand
Limestone or very limy sandstone
Oil or water sand flushed by fresh water

USES OF ELECTRIC LOGS

Obtaining accurate logs of old wells

In the older oil fields of the east there are many leases for which all records have been lost, and other leases for which well records are available, but there is great uncertainty as to which record goes with which well. The lack of records makes the cleaning out and rehabilitating of old wells impracticable. Several hundred dollars may be spent in cleaning out and shooting a well, but if an erroneous record is used and the shot is placed wrongly the work may be entirely lost. Levelling from a nearby well will not give accurate sand measurements. Finally the old drillers' logs are usually so incomplete and often inaccurate that a good job of rehabilitation can seldom be done even when they are available.

In numerous instances in Pennsylvania electric logs have facilitated the rehabilitation of old wells and saved the operators considerable sums of money. Figure 11 shows electric logs of four wells, located on a lease that had been abandoned for many years and was being revived for air repressuring. One of the wells (G) was drilled new and cored, but the others had been plugged and abandoned and no reliable records were available. Electric logs were made while the wells were being cleaned out with a light spudding machine. It will be noted that the core of well G was incomplete and a small bed of pay sand (marked A) was not cored. The electric log revealed the presence of this sand, and accurately reflected the position of the other permeable sections of the sand body, marked B, C, and D. The shot for well 9 had been ordered before the electric log was made on the basis of an old record which was believed to belong to this well, and which showed the sand nearly 20 feet too high. The shot would have resulted in nothing more than a bad cave and an expensive clean-out job without restoring the well to production, and the whole property might have been condemned for secondary recovery. Actually, as shown by the electric log, there was more sand in well 9 than in the cored well. Still farther to the east in well 8 sand bed A has further increased in thickness and has become an important part of the pay sand. Its presence would never have been suspected if the electric logs had not been made.

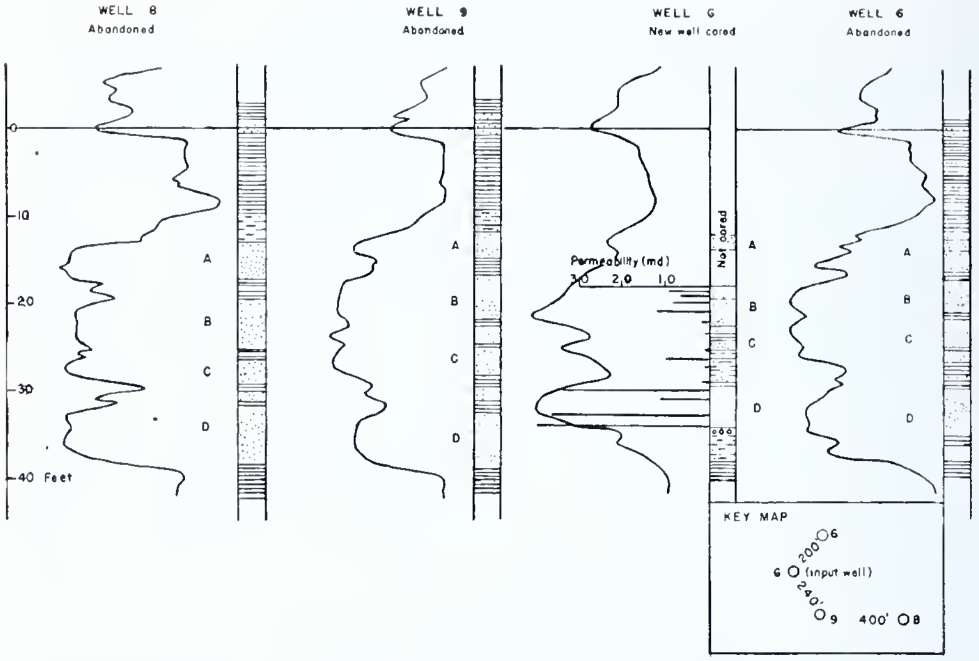

Figure 11. Potential logs of three old abandoned wells and one new cored well, showing exact determination of pay sand beds in old wells. Venango Third Stray sand.

Figure 12 is an electric log of the Atlas well, near Grand Valley, Pa. This well was drilled in 1867 and produced 15 barrels of oil daily with gas "sufficient to fire five boilers."[2] Other nearby wells being dry, it was soon abandoned, and it was not until ten years later that the productive Grand Valley pool was discovered a few miles to the south. The well was cleaned out in 1942, and the location of the pay sand (Venango Third Stray) is accurately shown.

Figure 13 shows electric logs of five wells, all but one of which were drilled to the Venango Third sand previous to 1910. Other wells showed that the Venango First sand was in places very rich and responded well to air drive. The old records did not show the position of the First sand, and it was therefore impossible to subject that sand to air drive as well as the Third. A bridge was set a short distance below the bottom of the First sand, the hole filled with water through the presumed horizon of the sand, and electric logs made. The potential curves showed the exact top and bottom of the pay section of the sand in each well. The resistance logs are quite variable, and no attempt was made to interpret them as the variations are principally due to the wall conditions in the old holes.

In one well it was found that waters bearing lime had been filtering out of the First sand for many years. They had deposited a crust of lime, generally called "gyp," on the wall of the hole below the top of the sand. When an electric log was made it indicated the top of the sand, but showed no detail in the sand and failed to show the bottom. The hole was bridged below the bottom of the sand, filled through the sand with broken

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[2] Carll, J. F. Oil well records and levels: Pennsylvania 2d Geol. Survey. Report. II p. 195 (1877).

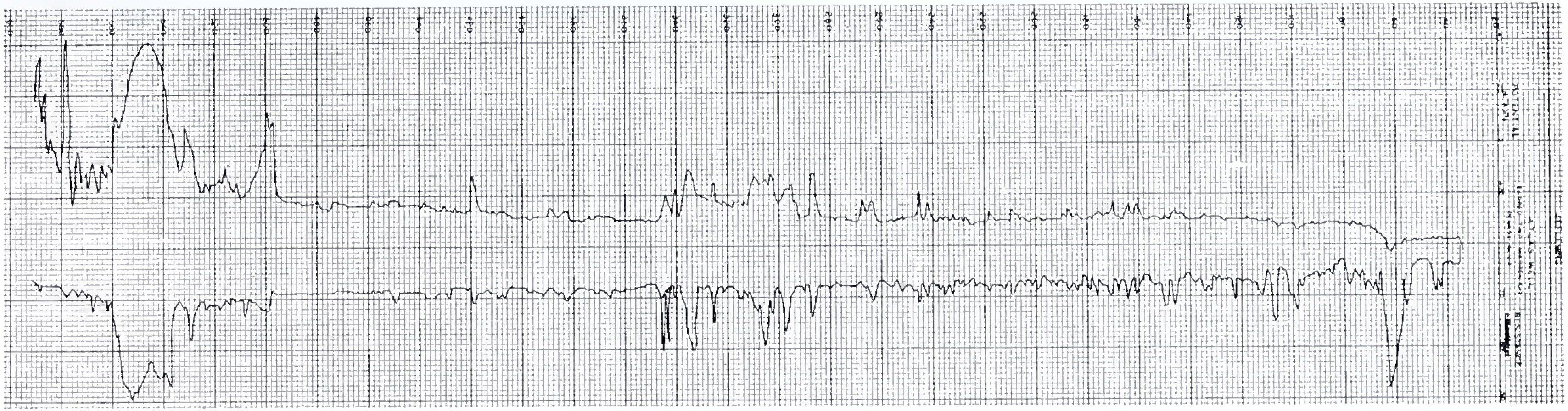

Figure 12. Electric log of Atlas well, Eldred Twp., Warren Co., Pa.

Well drilled in 1867 and abandoned about 1870. Cleaned out and electrically logged July 1942.

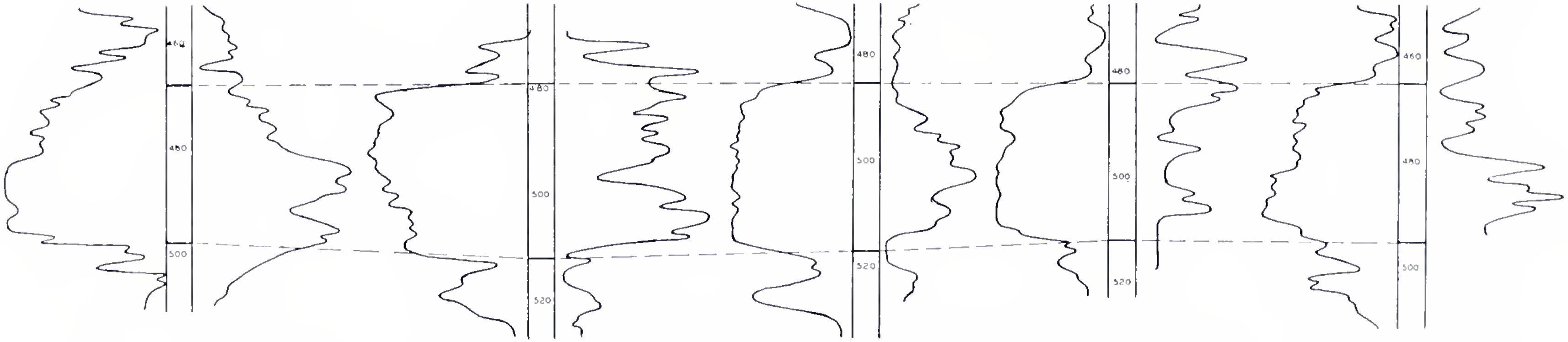

Figure 13. Location of upper pay sand which was not recorded when wells were drilled about 1890. Venango First sand.

rocks, and the rocks were then drilled out with the bit. This cleared the incrustation off the face of the sand and an excellent record was obtained.

Figure 14 is the electric log of a well in the Pioneer field of Venango County. The field was closely drilled in 1861 and 1862, and was very prolific. Subsequently it was abandoned, and considerable quantities of water gained access to the sand through improperly plugged wells. The sand is coarse and pebbly in certain beds, and much brackish water is produced with the oil. It was desired to determine which part of the sand was discharging the water, and whether it was possible to shut it off. The electric log shows a very high potential peak between 667 and 670 feet which is matched by a resistance low. This indicates that the sand between these depths probably is very permeable and contains salt water. The bed is in the middle of the sand body, and it is obviously not possible to shut the water off mechanically.

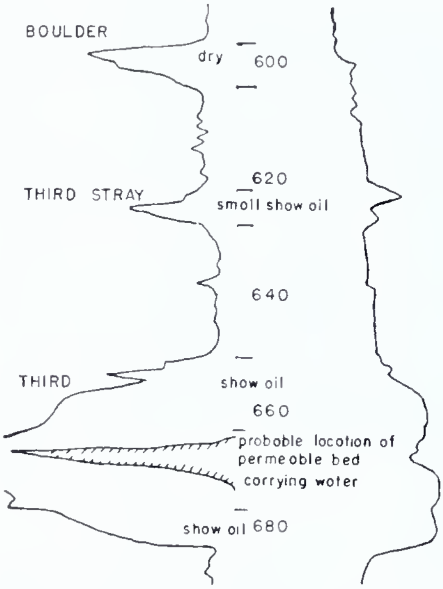

Figure 14. Electric log showing location of permeable bed carrying water. Venango Third sand.

Supplementing cores in setting packers and corrective shooting

The Venango sands which are being extensively repressured with air and gas in the Middle District of Pennsylvania are quite variable in permeability. If the air or gas is injected into the whole sand body at the same pressure it will enter only the most permeable beds and "bypass" the less permeable ones, which frequently contain considerable amounts of oil. This condition results in great operating inefficiency, unless the air can be injected into the different parts of the sand body at different pressures. It is possible to accomplish this by means of two to five or more packers, which engage the walls of the hole. Separate pipes conduct the air or gas to the different intervals between packers, and the volume of gas entering the different sections may be regulated at the surface. In order that these packers be properly set it is essential to know accurately the tops and bottoms of the different sections of the sand.

It is common practice to core the input wells with cable or "Baker" tools. Measurements of porosity, permeability, and oil and water saturation are made on the cores in the laboratory. Although these properties of a sand can be determined only by analyzing cores, the core record is not always entirely satisfactory as a means of locating packer settings. Much of the core is frequently lost, and the loss takes place principally in the softer and more permeable beds. This results in an erroneous picture of the permeability, and the depth of the samples may be in error by as much as several feet. If an electric log is made immediately after coring, the exact location of the shale breaks and points where the formation changes character can be determined, and the packers set in the best positions.

Although electric logs will, in general, not give the geological properties of the sand, such as porosity, permeability, and fluid content, in any one pool or district sands with similar geological properties will have similar electrical properties. Thus if a core analysis is compared with an electric log and the geological properties of the various sand sections compared with their electrical responses as shown by an electric log, it may be safely assumed that the same responses in a nearby well will correspond to the same properties. It is therefore possible both to core and electric log one well, and thereafter drill several wells without coring them, extrapolating the core data and determining the location of the changes in the sand by means of the electric log alone. If the electric logs change materially as wells are drilled farther and farther from the cored well, so that the sand changes can no longer be accurately correlated, it will be necessary to core another well to recalibrate the electric logs.

Cores are indispensable in estimating the recoverable reserves of a property and in deciding whether the sand is suitable for secondary recovery operations. Once this decision is made, however, the principal purpose of coring is to determine where the permeability changes in the sand occur. It is not necessary to know the absolute permeability of the different sections, since the gas input will be constantly regulated at the surface in any case. It appears that in many cases electric logs will indicate the relative permeability of the different sand sections and the best places to set packers.

In two wells where the air input in different parts of the sand was carefully determined it was found that the potential log gave as good an indication of the permeability as the core analysis (Fig. 15). Well A was cored and electrically logged. Two balloon packers spaced five feet apart were then run on a string of 2″ tubing and were set every five feet through the sand. At each setting the full line pressure was applied. After about 20 minutes the valve at the surface was closed, and the pressure inside the tubing read at one minute intervals. The rate of pressure decline was determined by the rate at which the air entered the sand, and therefore by the effective permeability of the sand section. On the right side of the diagram is plotted the percent drop in pressure four minutes after the valve was closed. It will be noted that the relative changes in actual permeability are better indicated by the potential log than by the core analysis. In a relatively impermeable zone between 605 and 620 feet there was one core sample with a permeability of about 800 millidarcies at a depth of 613½ feet. The electric log, confirmed by the packer test, indicates that the true position of this permeable zone was between 609 and 611 feet. The errors in the core analysis are doubtless due to (a) uncertainty in depth because of core loss, and (b) the permeability samples were not representative.

Well B was also cored and electrically logged. The top of the sand at 832 feet was missed by the drillers, and coring was not commenced until 840 feet. The electric log shows that the sand may be divided into three sections: a zone of moderate permeability from 832 to 842, a zone of slightly higher permeability from 842 to 856, and a zone of low permeability probably broken by shale from 856 to 864. Packers were set at irregular intervals, and the pressure required to inject 1,000 cubic feet of air per vertical foot of sand was determined. Air was allowed to enter for 24 hours and a second determination was made. The packer settings did not coincide with the changes in the sand, but they indicated that in the upper part about 300 pounds per square inch were required to inject 1,000 cubic

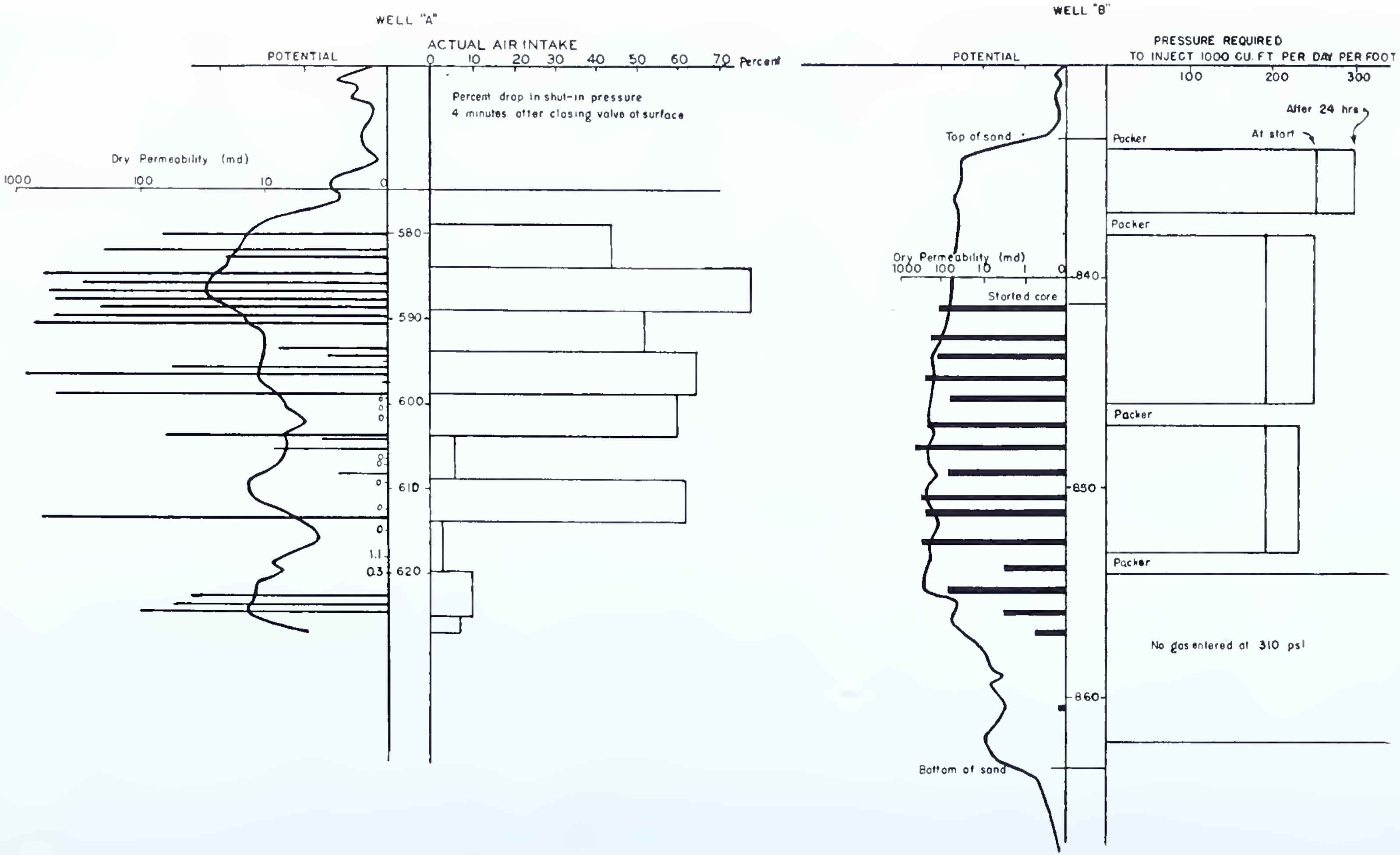

Figure 15. Comparison of potential log with core analysis and actual air input. Well A, Venango Third Stray sand; Well B, Venango Second sand.

feet per foot per day, in the middle section about 250 pounds per square inch, and in the lower section no air entered at all at 310 pounds, which was the highest pressure available.

The practice of corrective or "selective" shooting has become common in the secondary recovery of oil by water drive, and is also gaining favor in air drive operations. Shooting a short section of sand greatly increases its effective surface by the formation of radial cracks extending several feet back from the well. It is possible to shoot the relatively impermeable parts of the sand and greatly increase the volume of gas or water that they will take at a given pressure. The inequalities in permeability can thus in some measure be compensated. In selective shooting it is important that the sands be properly divided, since once the sand is shot it is impossible to change its input rate again.[1] The Bradford sand shows marked permeability changes in small beds only a few inches or less in thickness, and it is difficult to make an entirely reliable estimate of the effective permeability of each section from core or chip samples.

As this paper is written very few electric logs have been taken in the Bradford field, and these were taken with water in the hole, so that sharp changes in lithology did not show. Figure 16 is the log of a well in the Bradford field which was electrically logged and chip sampled. The potential curve shows that the sand may be divided into five permeable zones, of which only three were sampled, and also indicates the permeability of the zones. It will be noted that the position of the shale breaks is located with more assurance than was possible from the chip samples; in particular, shale is shown at the bottom of screw 12, while the electric log indicates that it is probably at the top. The electric log also suggests, but does not prove, that the single permeability determination of 0.32 millidarcies on screw 13 is lower than the true average permeability of the zone. It also shows that the lower zones which were not sampled are as good or better than the upper zones.

Figure 17 shows a comparison of an electric log and diamond core of the Bradford sand. The location of the shale breaks agrees in the electric log and core within the limits of accuracy of either; about six inches. The electric log located the pay horizons, but did not check the core analysis in indicating their relative permeability.

Difficulty in interpreting electric logs at Bradford has been experienced when the sands are partly flooded by water. The increased water content and decreased salinity affect both the potential and resistance curves. It is to be hoped that more experience and possibly modification in methods may make electric logging in the Bradford field an important supplement to coring and result in large savings to the operators.

No reason can be advanced at the present time to explain why the potential logs serve as an indication of relative permeability. It seems possible that the natural potential differences in the strata are caused by selective adsorption of the ions by the shales. In that case a sand containing much shale would have a lower (negative) potential than a sand containing little shale. The amount of shale in a sand is an important factor controlling its permeability. Work in Pennsylvania has indicated that the filtration potential is not a major factor in the potentials, and is not sufficient to explain the relationship between potential and permeability. In

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[1] Experiments with "selective plugging" media to reduce the permeability of certain specified sections of sand are in progress, but so far they have not been widely successful.

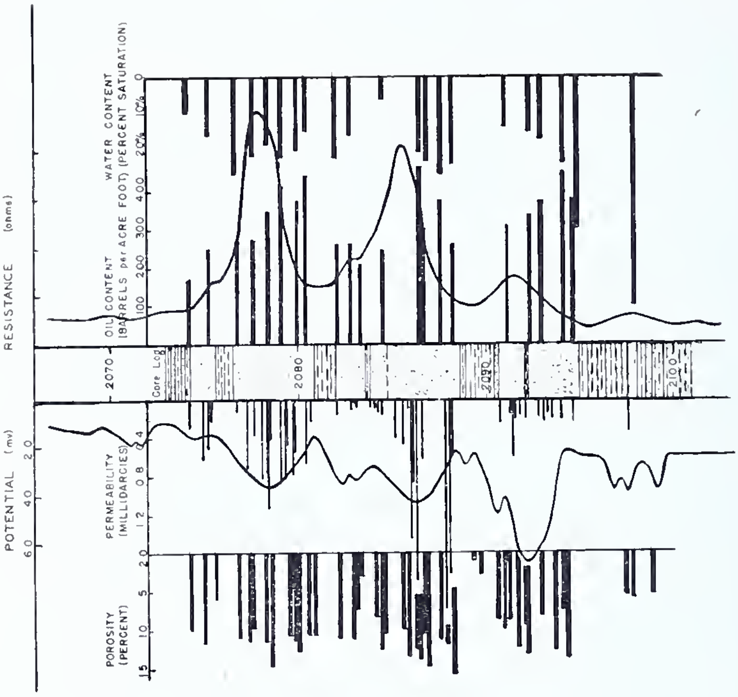

Figure 17. Comparison of electric log and diamond core. Bradford Third sand.

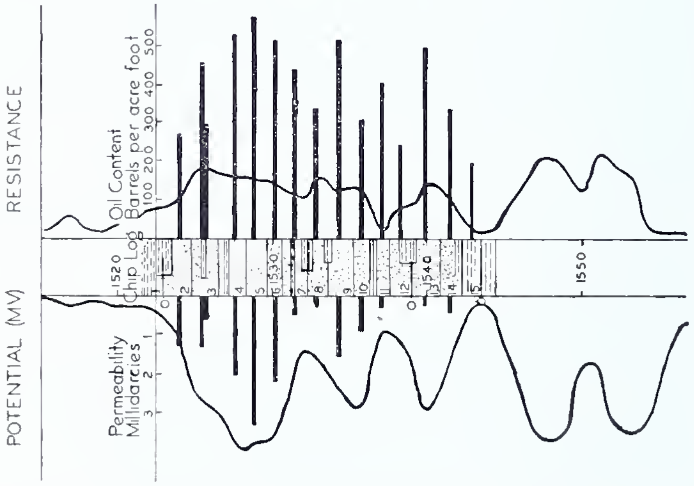

Figure 16. Comparison of electric log and chip sample analysis. Bradford Third sand.

most cases changing the pressure of water in the hole and therefore its rate of entry into the sand does not increase the potentials.

Locating pay sands not noticed by the drillers

One of the principal uses of electric logs in the western fields is the location of pay sands that cannot be noticed while drilling with rotary tools. Most cable tool drillers in Pennsylvania would indignantly deny that they ever failed to note and record a sand that could produce oil. However, a very surprising number of electric logs have shown pay sand that was not recorded by the drillers, as many of the preceding examples show.

Figure 18 is the electric log of a semi-exploratory well to test the Gray sand in eastern Venango County. The Gray sand is separated from the usually unproductive Third sand by a thin shale break. The drillers noted a fair oil show between 1085 and 1108, with a shale break between 1108 and 1110. The rest of the Gray sand was drilled through and the Third sand was encountered between 1120 and 1126. The section between 1085 and 1108 was considered the Gray sand, and the well was shot only in this interval. The electric log indicates that the section from 1110 to 1118 was as well saturated as the preceding section, and if this section had also been shot the productivity of the well might have been considerably increased.

Figure 19 is the electric log of an air input well in the Venango Third sand. The drillers reported the top of the sand at 859 feet and coring was commenced at that point. The total sand thickness was nearly ten feet less than in nearby wells, so an electric log was made and found that the top of the sand was really at 850 feet. The log indicated that the upper section of the sand between 850 and 859 feet was the most permeable. The potential log was higher in this interval, and the resistance log was low, indicating that drilling water was probably entering the sand.

Many wells in the southwestern part of Pennsylvania and in West Virginia record only 5 to 10 feet of pay sand although the total sand section may be several times that thickness. The "pay" interval was probably the permeable part of the sand that made a good show while drilling. The production history of these pools suggests that quite possibly the rest of the sand body may also have been oil bearing, and if the sand were to be

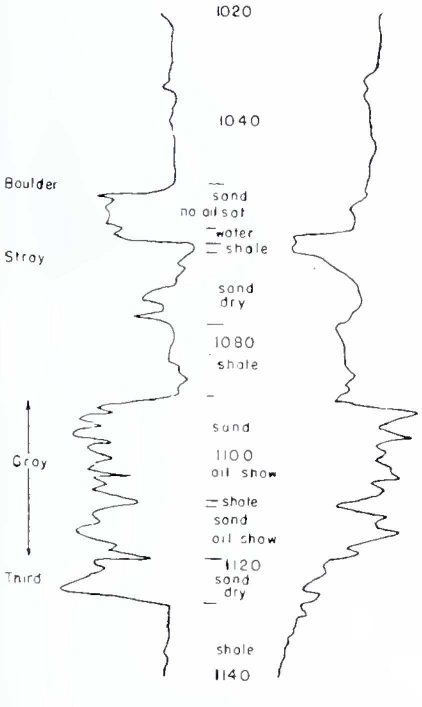

Figure 18. Distinction between oil-bearing and barren sands in semi-exploratory well. Venango Gray and Third sands.

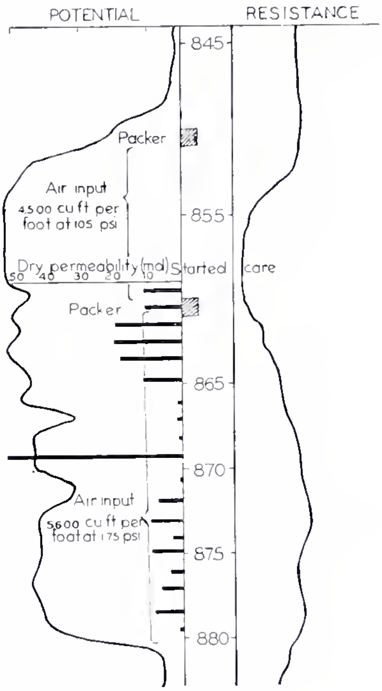

Figure 19. Determination of top of sand missed by drillers. Venango Third sand.

shot throughout its entire thickness large additional quantities of oil might be recovered.

Geological correlation

Another important use of electric logging in the western fields is the correlation of geological horizons from well to well. Where oil is found only in domes or anticlines it is important to know the sea-level elevation of the sand in each well in order to determine its position on the structure and the distance from the water which surrounds and often underlies such pools. Where water is present in the lower part of the pay sand it is important to stop drilling before the water-bearing sand has been penetrated. Geological horizons may be identified and followed from well to well by the characteristic shapes and appearances of the peaks on the electric logs. It is usually not at all necessary to know what sort of rock causes these peaks; the peaks themselves provide the best possible means of correlation.

In Pennsylvania, where position on structure has little or no effect on the accumulation of oil, the utility of accurate geological correlations is not apparent to most operators. However, geological correlations are very important to prospecting for new pools. Where there are no surface indications which may guide the wildcatter to a new pool, it is necessary to assemble all available information from wells. It has been found, as a result of very detailed work in the northern fields of Pennsylvania, that the oil occurs in lens- or pod-shaped bodies of sand at numerous different horizons. If all the irregular sand bodies at one particular horizon are plotted on a map and studied separately, it is found that the sand bodies line up into well defined trends and have many characteristic features in common. Both the trends and habits of the bodies at one horizon differ from those of sands at a different horizon. In order to seek extensions or new sand bodies intelligently it is necessary to determine which horizon the producing and possible sand bodies belong to, which is practically impossible with drillers' logs alone. Therefore, it is hoped that with the more general use of electric logging in Pennsylvania it will be possible to solve important stratigraphic problems which have defied solution for more than sixty years. Figure 20 shows how electric logs were used to correlate the oil sands in the Titusville Quadrangle.

ACKNOWLEDGMENTS

The introduction of electrical logging into the eastern oil fields is largely due to the interest and foresight of a small group of operators in the Titusville-Oil City district. They supported and encouraged the experiments by the Pennsylvania Geological Survey which led to a realization of some of the ways in which electrical logging may be applied to the problems of the secondary recovery of oil. The illustrations in this report were chosen from many hundreds of runs using different circuits and types of equipment. The oil producers made their wells available for this work, and the drillers and crews showed genuine interest and very great patience.

The Halliburton Oil Well Cementing Co. has shown a sincere interest in the conditions and problems of the eastern fields, and cooperated fully with the producers and the Geological Survey. The writer is very deeply indebted to Mr. H. Guyod of that organization, who assisted materially in the preparation of this report.

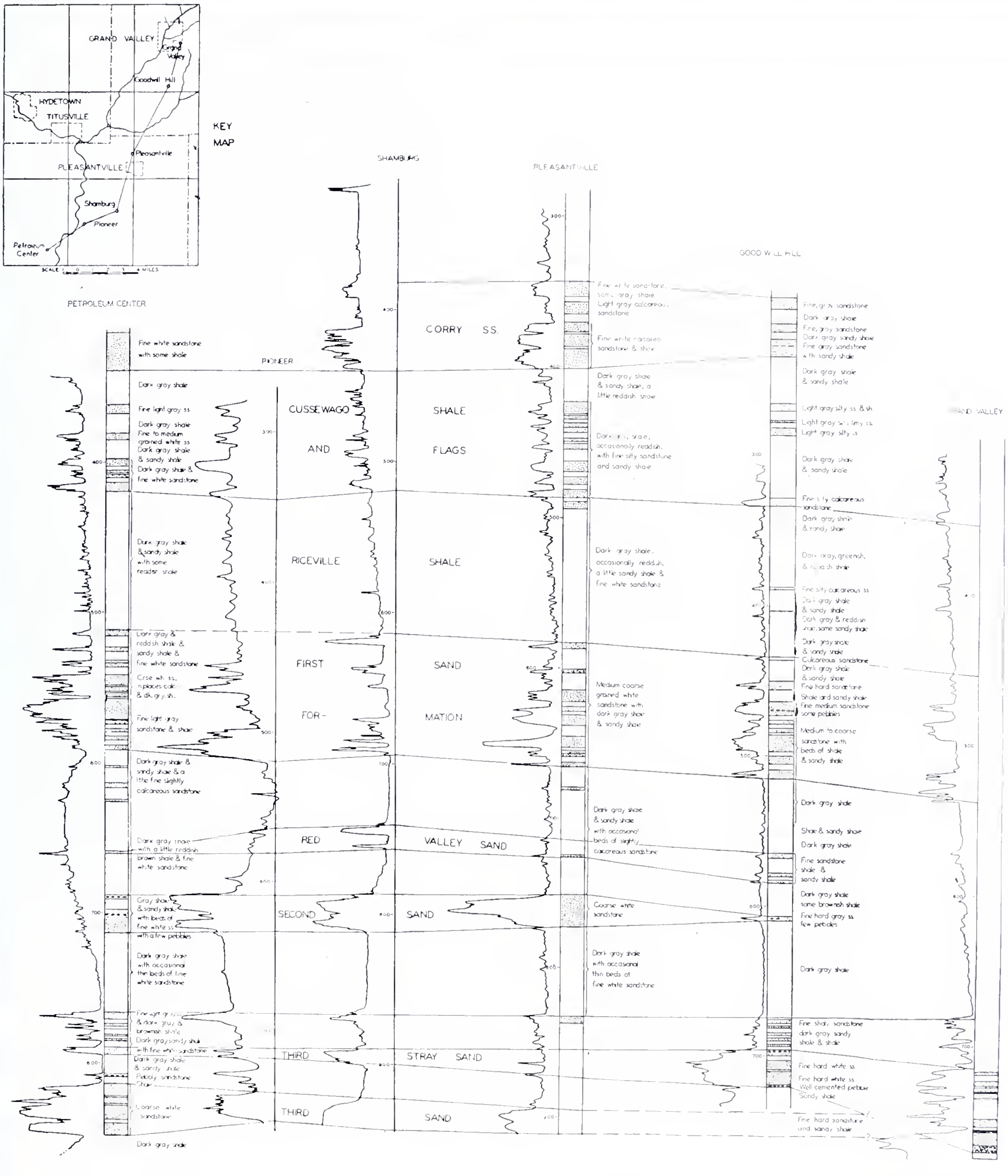
GRAND VALLEY
Grand Valley
Goodwill Hill
HYDETOWN
TITUSVILLE
Pleasantville
PLEASANTVILLE
Shamburg
Pioneer
Petroleum Center
SCALE 1 0 1 2 3 4 MILES
KEY MAP
PETROLEUM CENTER
PIONEER
SHAMBURG
PLEASANTVILLE
GOOD WILL HILL
GRAND VALLEY
CORRY SS.
CUSSEWAGO AND SHALE AND FLAGS
RICEVILLE SHALE
FIRST SAND FORMATION
RED VALLEY SAND
SECOND SAND
THIRD STRAY SAND
THIRD SAND
300
400
500
600
700
800
Fine white sandstone with some shale
Dark gray shale
Fine light gray ss
Dark gray shale
Fine to medium grained white ss
Dark gray shale & sandy shale
Dark gray shale & fine white sandstone
Dark gray shale & sandy shale with some reddish shale
Dark gray & reddish shale & sandy shale & fine white sandstone
Crse wh. ss, in places calc. & dk. gry. sh.
Fine light gray sandstone & shale
Dark gray shale & sandy shale & a little fine slightly calcareous sandstone
Dark gray shale with a little reddish brown shale & fine white sandstone
Gray shale & sandy shale with beds of fine white ss with a few pebbles
Dark gray shale with occasional thin beds of fine white sandstone
Fine light gray ss & dark gray & brownish shale
Dark gray sandy shale with fine white sandstone
Dark gray shale & sandy shale
Pebbly sandstone
Shale
Coarse white sandstone
Dark gray shale
Fine white sandstone, some gray shale
Light gray calcareous sandstone
Fine white calcareous sandstone & shale
Dark gray shale & sandy shale, a little reddish shale
Dark gray shale, occasionally reddish, with fine silty sandstone and sandy shale
Dark gray shale, occasionally reddish, a little sandy shale & fine white sandstone
Medium coarse grained white sandstone with dark gray shale & sandy shale
Dark gray shale & sandy shale with occasional beds of slightly calcareous sandstone
Coarse white sandstone
Dark gray shale with occasional thin beds of fine white sandstone
Fine, gray sandstone
Dark gray shale
Fine, gray sandstone
Dark gray sandy shale
Fine gray sandstone with sandy shale
Dark gray shale & sandy shale
Light gray silty ss & sh.
Light gray silty limy ss
Light gray silty ss
Dark gray shale & sandy shale
Fine silty calcareous sandstone
Dark gray shale & sandy shale
Dark gray, greenish, & reddish shale
Fine silty calcareous ss
Dark gray shale & sandy shale
Dark gray & reddish shale, some sandy shale
Dark gray shale & sandy shale
Calcareous sandstone
Dark gray shale & sandy shale
Fine hard sandstone
Shale and sandy shale
Fine medium sandstone some pebbles
Medium to coarse sandstone with beds of shale & sandy shale
Dark gray shale
Shale & sandy shale
Dark gray shale
Fine sandstone shale & sandy shale
Dark gray shale some brownish shale
Fine hard gray ss few pebbles
Dark gray shale
Fine shaly sandstone dark gray sandy shale & shale
Fine hard white ss
Fine hard white ss
Well cemented pebble
Sandy shale
Fine hard sandstone and sandy shale
?

Figure 20. Columnar sections in Titusville district showing use of electric logs in correlating sands.